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MODELING THE INNOVATION RESONANCE IN INDUSTRIALIZED REGIONS[1]

The main objective of this article is to provide a rationale for mathematical models describing the innovation resonance in industrialized regions. The article presents a thorough analysis of trends in the development of Russian industrialized regions, which is then used as the basis to advance and test several hypotheses, such as the hypothesis of uneven economic development in different types of industrialized regions (regions strengthening their industrial status, newly industrialized regions and deindustrialized regions), hypothesis of individual characteristics in the development of certain types of industrialized regions, hypothesis of the state acting as catalyst in innovation dynamics, hypothesis of innovation resonance existing in economic system. The authors propose the methodology of innovation resonance, describe the conditions required for the emergence of resonance in the economic system, and provide a rationale for the types of resonance response. The main methods used in this article are as follows: resonance control method, reproduction method, methods of economic and mathematical modeling. The authors propose a mathematical formalization for the mechanism of innovation resonance in the regional industrial system, including: a) A model for generating investment by industrial sectors and reproduction sectors; b) Dynamic multi-sector reproduction model; c) Adaptive management model for innovative self-development of the regional industrial system; g) A model for the sustainability of innovation dynamics and expanded reproduction. The authors study the innovation resonance in Russian industrialized regions. In the context of innovation resonance, the authors review the functional industrial policy of a typical industrialized region and resonance responses related to its implementation. The results of the study presented in the article can be used in substantiating the mechanisms of regional industrial policy, and to assess the regulatory impact of existing regulatory and legal acts.

Keywords: innovation resonance; industrialized regions; functional industrial policy; state support measures

Problem statement: trends in the development of industrialized regions

The trends of global economic development suggest that there is no alternative to reindustrialization [1, 2, 3, 4], the defining vector of which is the development of high-tech industries both on the scale of national economies [5, 6, 7, 8] and within individual, primarily, industrialized regions [9, 10, 11, 12, 13].

The industrialized regions are the core of development in any national economy. It is in the industrialized territories that occur transformation of the technological structure of the economy, change of techno-economic paradigms, modernization of production and consumption. The industrialized regions were among the first to enter the phase of industrial development and, as a result, today, many of them have a poorly diversified economic structure and specific characteristics of internal territorial structures. Not all industrialized regions can or should become the engines of technological development. Some industrialized regions are experiencing an objective process of deindustrialization, associated with a significant decline of the share of industrial sector in the Gross Regional Product (GRP), and are evolving into a consumer type economy. Other industrialized regions are going through reindustrialization, associated with the change in the share of traditional industries amid the rise of high-tech production sector.

To identify the particular aspects of deindustrialization and reindustrialization in the Russian regions, we have studied the regions where the share of processing industries in GRP exceeded 25 % in 2004–2012. The use of the single-criterion method for classifying the regions as industrialized has been sufficiently substantiated in scientific papers of the Council for Study of Productive Forces [14], regulatory documents of the Ministry of Regional Development of the Russian Federation, analytic and scientific literature [15, 16].

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In this study, we deliberately did not use the share of the entire industrial sector in GRP as a criterion for classifying the regions as industrialized, because in such case the industrialized regions would automatically include raw-material regions with high share of extractive sector (Tyumen Region, Orenburg Region, Kemerovo Region, Tomsk Region, Magadan Region, Sakhalin Region, Komi Republic, Tatarstan, Udmurtia, Sakha Republic, etc.). The use of a more rigorous criteria for classifying the regions as industrialized allows selecting only those regions where it is possible to build high-tech industries with significant value added.

The study of Russian regions was conducted in 2004–2012 (see Table 1). It is difficult to analyze the period prior to 2004, because the share of processing industries was separated in the statistical accounting only following the transition from the concept of OKONKh (All-Russian Classifier of National Economy Sectors) to the one of OKVED (All-Russian Classifier of Economic Activities).

Table 1

Share of Manufacturing Industries in GRP, %

Subject of the Russian Federation	2004	2005	2006	2007	2008	2009	2010	2011	2012
Vladimir Region	33.2	34.3	35.4	33.4	34.1	30.1	31.5	31.0	30.3
Kaluga Region	28.4	27.8	27.8	29.8	31.9	29.2	33.5	38.2	40.2
Lipetsk Region	63.2	55.4	55.6	52.4	53.5	42.6	40.9	39.2	32.1
Moscow Region	27.4	25.2	27.0	25.4	23.7	21.7	20.9	23.1	17.8
Ryazan Region	23.6	23.1	23.3	26.6	25.5	24.8	27.5	29.5	26.6
Tula Region	33.9	36.6	34.2	33.0	35.7	27.5	30.1	35.3	34.1
Yaroslavl Region	36.6	32.1	27.2	28.3	27.0	25.0	24.9	27.0	26.7
Ivanovo Region	28.1	20.7	20.1	22.5	24.7	18.2	21.6	22.9	19.6
Vologda Region	45.4	46.6	46.1	46.0	50.5	36.4	38.1	41.1	36.1
Leningrad Region	31.9	29.1	28.5	27.6	26.4	29.7	24.6	26.1	22.8
Murmansk Region	21.8	25.5	25.3	27.9	15.8	16.7	17.5	15.5	13.3
Novgorod Region	33.2	34.6	34.0	32.6	34.4	32.2	30.2	32.9	35.8
Astrakhan Region	24.9	27.7	23.4	21.2	30.7	14.8	17.9	16.9	19.2
Volgograd Region	20.6	26.6	27.5	26.9	30.6	23.1	26.7	26.2	26.6
Republic of Bashkortostan	29.6	27.7	28.8	27.7	28.5	21.7	28.0	28.9	37.2
Republic of Mari El	20.8	20.2	18.7	21.6	23.4	21.4	28.2	28.3	29.8
Republic of Mordovia	24.4	24.4	25.2	23.9	26.1	21.5	25.6	23.0	22.9
Chuvash Republic	23.4	23.0	25.5	28.0	29.9	24.8	27.0	25.5	26.3
Perm Territory	24.8	29.4	27.5	30.7	34.9	26.8	29.9	34.0	31.4
Kirov Region	22.2	21.1	22.9	24.9	26.4	20.4	22.8	25.6	25.5
Nizhny Novgorod Region	31.8	30.6	32.3	32.1	31.9	26.5	30.8	29.9	30.3
Samara Region	32.3	29.9	28.4	28.4	25.8	20.5	24.7	25.5	25.0
Ulyanovsk Region	25.7	19.8	20.5	22.0	21.4	17.5	20.8	21.8	22.1
Sverdlovsk Region	35.1	31.5	33.5	33.3	33.1	27.8	29.1	28.4	27.1
Chelyabinsk Region	45.2	41.4	39.0	41.0	39.2	33.6	36.2	36.2	35.8
Krasnoyarsk Territory	47.8	47.1	52.4	50.2	37.6	34.4	34.5	33.8	30.7
Irkutsk Region	22.9	26.1	27.8	18.3	17.4	15.7	16.3	15.4	13.6
Omsk Region	53.1	47.8	40.6	38.3	38.9	35.9	34.8	37.5	38.6
Russia	20.4	18.5	18.7	19.7	19.3	17.1	17.7	18.0	17.3

Overall, in Russia, we observe an objective process of deindustrialization, the decline in the share of processing industries from 20.4 % in 2004 to 17.3 % in 2012 (Fig. 1). Of course, this process could be considered in the theoretical context of the post-industrial economy (J. Galbraith, D. Bell, A. Toffler, and others) or "tertiarization" concept of C. Clark and J. Fourastié, if the labor productivity in the Russian industrial sector had not been so catastrophically low. Such researchers as T. Gurova and A. Ivanter note that Russia significantly lags behind the leading industrial powers (and not only them) in terms of processing industry output per capita. In Russia, this figure is $504 while in the United States it is

11 times higher; in Singapore and Japan, it is 16 times higher. It is also higher in China, Brazil, Greece, Thailand, Uruguay, and other countries without a traditionally developed industrial sector [17]. Across a wide range of processing industries, the figures for Russia are also low, except for the production of precious and non-ferrous metals. For most other positions, Russia significantly lags behind: in the production of electric motors, generators, and transformers, it lags behind the United States by 2.6 times, Germany—5.2 times, Finland—14.6 times; in the production of clothing, it lags behind the United States by 5.9 times, Germany—4.4 times, South Korea—16.4 times, Brazil—2 times; in the production of general engineering goods, it lags behind the United States by 10.4 times, Germany—17.8 times, South Korea—8.8 times; in the production of pharmaceutical medicines and substances, it lags behind the United States by 66 times, Germany—31.5 times, South Korea—18 times [17].

In its territorial aspect, the process of deindustrialization in Russia was proceeding unevenly during 2004–2012. While in 2004, 18 regions had been classified as industrialized, by 2012 their number was already 20. Today, we can build the following ranking of Russian industrialized regions (Fig. 2). The largest share of processing industries in their GRP have Kaluga Region (40.2 %), Omsk Region (38.6 %), and the Republic of Bashkortostan (37.2 %). The lowest value of this indicator among industrialized regions have Chuvash Republic (26.3 %), Kirov Region (25.5 %), and Samara Region (25.0 %).

At the same time, there was a significant change in the composition of industrialized regions' group.

In the reviewed period, four traditionally industrialized regions have lost their industrialized status, including Moscow Region (decline in the share of processing industries in GRP from 27.4 % in 2004 to 17.8 % in 2012), Ivanovo Region (decline from 28.1 to 19.6 %), Leningrad Region (decline from

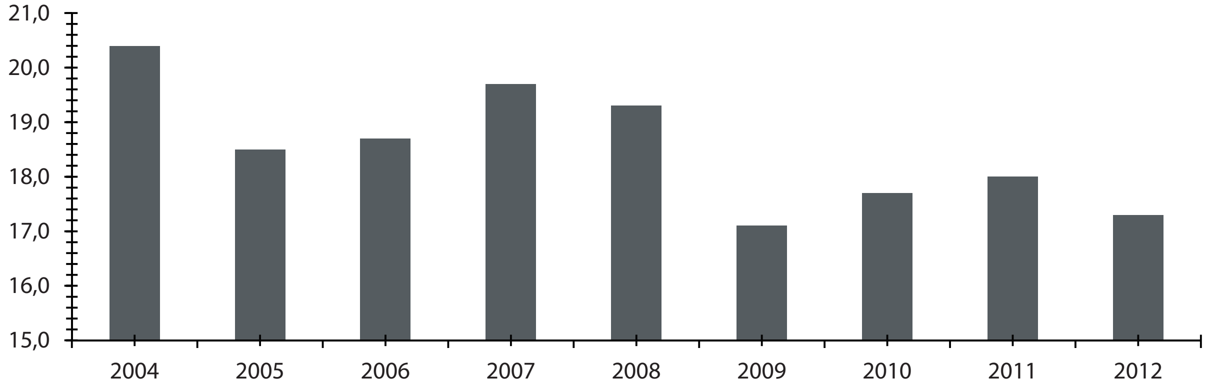

Fig. 1. *The Deindustrialization of the Russian Economy: Declining Share of Processing Industries in GDP*

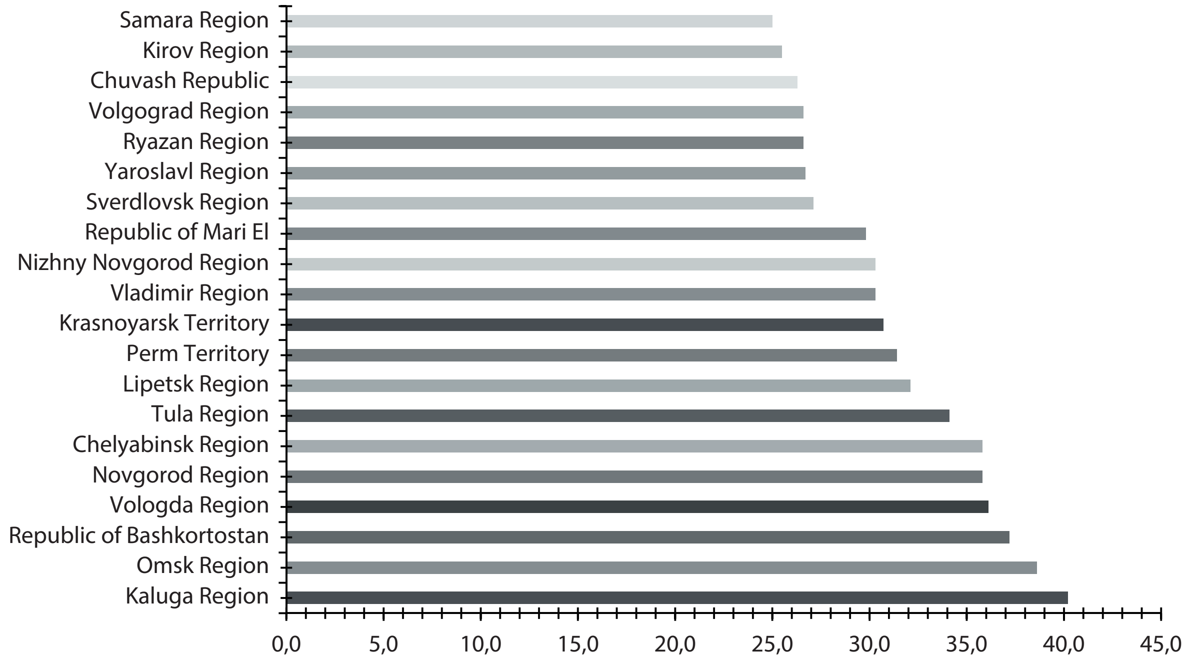

Fig. 2. *The Ranking of Russian Industrialized Regions by Share of Processing Industries in their GDP*

31.9 to 22.8 %), and Ulyanovsk Region (decline from 25.7 to 22.1 %). In these regions, the process of deindustrialization was accompanied by a significant rise of service sector amid the economic growth, improved quality of life and more active investment process. In other words, the deindustrialization here can be viewed as the optimization of industrial sector share. The experience of these regions shows that the deindustrialization can be accompanied, on the one hand, by the productivity growth and, on the other hand, by the establishment of extensive service infrastructure in the area of logistics, product promotion, innovative services and brand creation.

In the reviewed period, another four traditionally industrialized regions have strengthened the position of processing industries in the gross value added of the region—these are Kaluga Region (increase of share from 28.4 to 40.2 %), the Republic of Bashkortostan (increase of share from 29.6 to 37.2 %), Novgorod Region (increase of share from 33.2 to 35.8 %) and Tula Region (increase of share from 33.9 to 34.1 %). The large-scale investment projects to modernize the traditional sectors, as well as the establishment of new enterprises, allowed to speak about new industrialization in these subjects of the Russian Federation.

The period of 2004–2012 saw the emergence of six newly industrialized regions with increased share of processing industries in GRP—these are Perm Territory (increase from 24.8 to 31.4 %), the Republic of Mari El (increase from 20.8 to 29.8 %), Volgograd Region (increase from 20.6 to 26.6 %), Kirov Region (increase from 22.2 to 25.5 %), Chuvash Republic (increase from 23.4 to 26.3 %), and Ryazan Region (increase from 23.6 to 26.6 %). The growing importance of processing sector in the economy of these regions is primarily associated with the implementation of major investment projects.

Finally, in the majority of traditionally industrialized regions, the development was accompanied by negative deindustrialization. These regions include Lipetsk Region (decline from 63.2 to 32.1 %), Krasnoyarsk Territory (decline from 47.8 to 30.7 %), Omsk Region (decline 53.1 to 38.6 %), Yaroslavl Region (decline from 36.6 to 26.7 %), Chelyabinsk Region (decline from 45.2 to 35.8 %), Vologda Region (decline from 45.4 to 36.1 %), Sverdlovsk Region (decline from 35.1 to 27.1 %), Samara Region (decline from 32.3 to 25.0 %), Vladimir Region (decline in the share of processing industries in GRP from 33.2 to 30.3 %), and Nizhny Novgorod Region (decline from 31.8 to 30.3 %). Today, these old industrialized regions face serious constraints to further development, caused by abnormal co-existence of multiple techno-economic paradigms, i.e. the simultaneous reproduction of multiple technological paradigms ranging from the third to the fifth paradigm. [18]

The structural and technological shifts in the economy of old industrialized regions have been largely happening spontaneously under the influence of changes in the current economic environment, which led to the critical situation in the technological structure of production. This resulted in a bias towards the dominance of low and medium-level technology industries that are energy-intensive and environmentally flawed. In addition, given the overall resource constraints, the simultaneous expanded reproduction of multiple technological paradigms led to lower growth rates in each of these paradigms, including the fifth and sixth, and slowed down the structural shifts.

Thus, the differentiation of industrialized regions allows advancing a hypothesis that not all industrialized regions can, in the long run, become the engines of economic growth: each industrialized region has its own individual development path that takes into account its resource, structural and institutional capacity. The modeling of such individual path can be based on the models of innovation resonance.

Methodology of Innovation Resonance

To solve the problem of overcoming the abnormal co-existence of multiple techno-economic paradigms and building the high-tech sector in industrialized regions, we proposed the methodology of innovation resonance, which refers to the phenomenon of accelerated development in the economic system exposed to wave dynamics as a result of periodic change in the innovation and technology parameters through catalytic mechanism built into the Science-State-Business relationship, a triad synergistic system.

The formation of core technologies in a new techno-economic paradigm is a non-linear process of restructuring the technological chains of previous stages [20]. At the same time, the economic growth is seen only as a result of innovation resonance, while its cause is the alignment between the intensity produced by the impact of specific actions made by economic agents in the area of technological development and the intensity of economic dynamics.

Several studies have proved the feasibility of using a universal logistic approach based on S-curves to model the economic and technological dynamics. The article of A. I Yablonsky demonstrated the possibility of using *S*-curves and Lotka—Volterra equations to model the processes of technological development [21]. The experimental studies conducted by V. M. Polterovich and A. A. Khenkin showed that the process of diffusion expressed as a share of output at a specific technological level, or the share of companies that have mastered the market of new products, can also be described by the logistic curve or its modifications [22]. The use of positive properties of the logistic curve to describe the life cycle of macrogenerations (product innovations in the US economy that determine the dynamics of GDP) was proposed in the article of V. I. Maevsky [23].

The technological dynamics can be described by equation (1), where *Y*(*t*) is a function that describes the outcome (effect) of innovation development; *r* is a value that describes the speed of innovation development and determines the slope of *S*-curve; *P* is a positive value that establishes the upper limit of innovation development (the maximum value of function *Y*(*t*), capacity); *C* is the value that defines the shift of *S*-curve relative to *X*-axis.

$$Y\left(t\right)=\frac{P}{1+Ce^{-rt}}. \tag{1}$$

Figures 3 and 4 show the graphs of two functions and their derivatives before and after the functions have been brought to resonance. It is clear that to identify the resonance conditions, we need to define the parameter *t*, under which the derivatives of functions reach their peak at one point, by expressing it through parameters *C* and *r* (2).

$$\frac{-\ln\frac{1}{C_1}}{r_1}=\frac{-\ln\frac{1}{C_2}}{r_2}=t^*. \tag{2}$$

It becomes clear that by adjusting the slope of *S*-curve (parameter *r*) and its shift relative to *X*-axis (parameter *C*), we can achieve the resonance of functions [23].

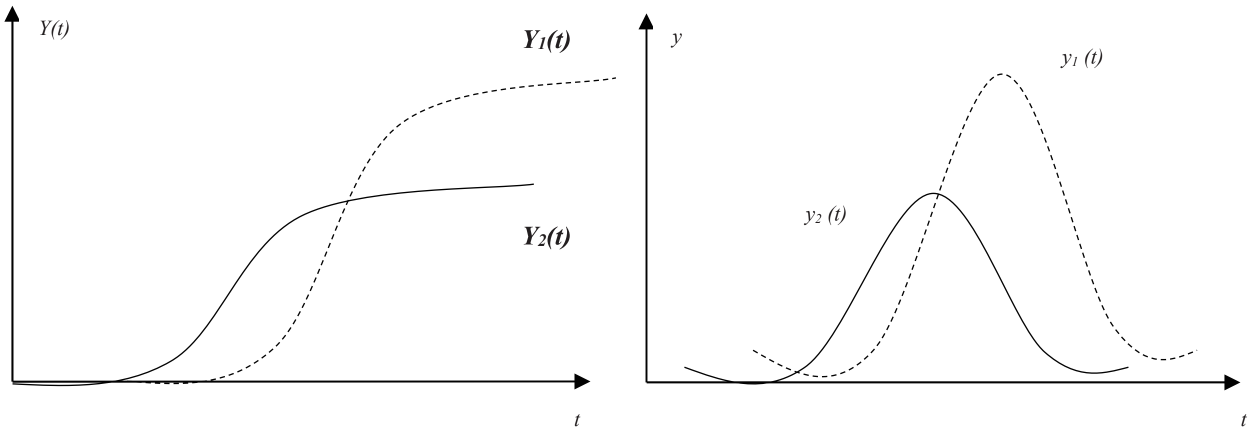

Fig. 3. *The graphs of functions $Y_1(t)$ and $Y_2(t)$ and their derivatives before the functions are brought to resonance*

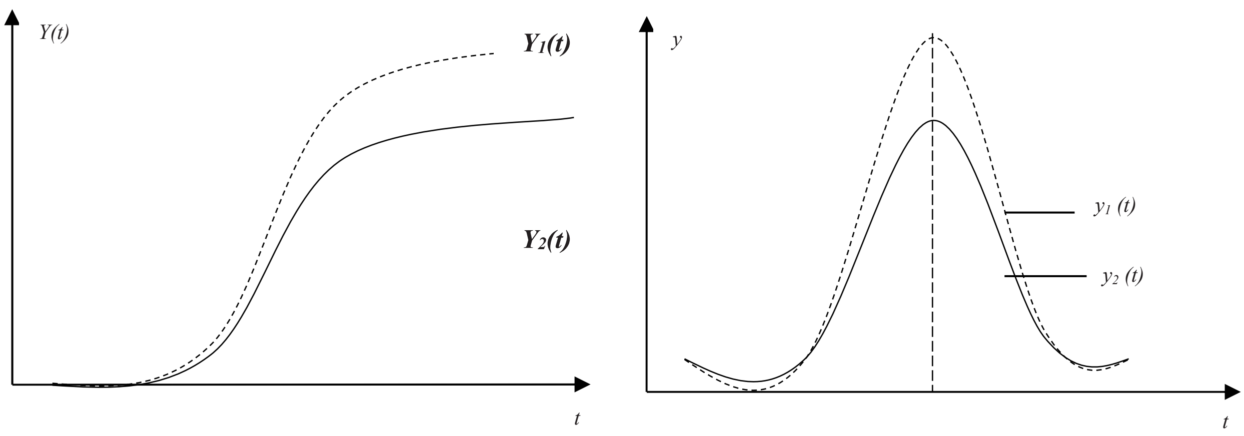

Fig. 4. *The graphs of functions $Y_1(t)$ and $Y_2(t)$ and their derivatives after the functions are brought to resonance*

While controlling the parameter *r*, that determines the response of the market demand for technological innovation, is rather difficult given a significant amount of subjectivity on the part of consumers, the parameter *C*, that describes the effectiveness of state institutions in creating the conditions for the spread of innovation, can be viewed as the main controlled parameter in achieving the innovation resonance [25].

In the context of innovation resonance, we reviewed the functional industrial policy (parameter *C*), the renaissance of which is noted today by many experts [26, 27]. In 2013, two key reports have been released on industrial policy. The first was the report Beyond Industrial Policy: Emerging Issues and New Trends published by OECD. The second was the report Towards Knowledge-Driven Reindustrialization published by the European Commission, which suggests a surge of interest in industrial policy. This can be explained by the fact that, according to some experts, a new technological paradigm will not begin before 2030 (even in the developed countries). So, there is a need to continue using the existing techno-economic paradigm which, in turn, is only possible with effective industrial policy tools.

While exploring the phenomenon of innovation resonance in the context of the above definition, some additional hypotheses have been advanced on the conditions required for emergence of resonance response from the economic system to changes in the technology area: 1) The resonance response emerges when there is a third element, the catalyst, in the triad structure of relationships within the innovation system; a support institution can act as the catalyst in the form of special motivation mechanism built by businesses in a competitive environment or created by the state; 2) The resonance response is a positive feedback from innovative self-development pushed to the limits of capacity (capacity utilization) of specific techno-economic system.

The theoretical research proved that the innovation resonance is parametric. The understanding of resonance as a phenomenon that occurs only in a rhythmic external impact on the fluctuating system, where the frequency of external impact matches the frequency of the system, was rejected. This is due to the fact that, in an open economic system, it is rather difficult, if not impossible, to achieve a periodic external impact with the necessary rhythm, because such external impact relates to economic policies pursued by the actors that are outside the analyzed system.

In addition, there is an objective understanding that any modulation of parameter *C* (in this case, the use of functional industrial policy tools) could not "shake" the economic system that is in a state of rest and in a position of equilibrium. For excitation of parametric innovation resonance, the economic system should make its own fluctuations associated with the economic environment cycles, medium-term business cycles, and Kondratiev long waves. As a result, it was proposed to describe the phenomenon of innovation resonance, where the increasing dynamics are caused not by the external impact but by the parameters of the system itself, by using the differential equations of parametric resonance in linear and nonlinear systems.

In parametric resonance, the state of equilibrium in a system becomes unstable, and the exit from such state takes the form of fluctuations with a progressively increasing amplitude. An important point in this regard is the analysis of threshold values and valid intervals as well as the conditions for absorption of fluctuations and dynamic cancellation of negative economic dynamics that could lead the system to a recession.

The complete mathematical model of qualitative resonance responses of the economic system to control actions was developed based on "Science—Technology—Market" innovation cycle. In this context, it may be noted that considerable resonance responses occur at the points of transition from one area to another. In this regard, we distinguish three types of resonance responses: scientific and technological, market and technological, and integrated (Fig. 5).

The mechanism of innovation resonance of the regional industrial system is based on combination and interaction of state regulation, innovative business and its infrastructure, as well as the fundamental and applied research in the area of high technology. The difficulty of creating such mechanism lies primarily in identifying the ways and means to ensure the effective implementation of scientific and technical programs aimed at developing and mastering the knowledge-intensive and resource-efficient technologies and to allow the industrial enterprises to carry out the economic production cycle in the expanded reproduction mode. In this regard, the mechanism of innovation resonance of the regional industrial system should include the following elements (Fig. 6):

1. The Model of Investment Formation by Industry Sectors and Reproduction Sectors. The investment resources have two investment areas: 1) Replenishment and modernization of fixed capital within

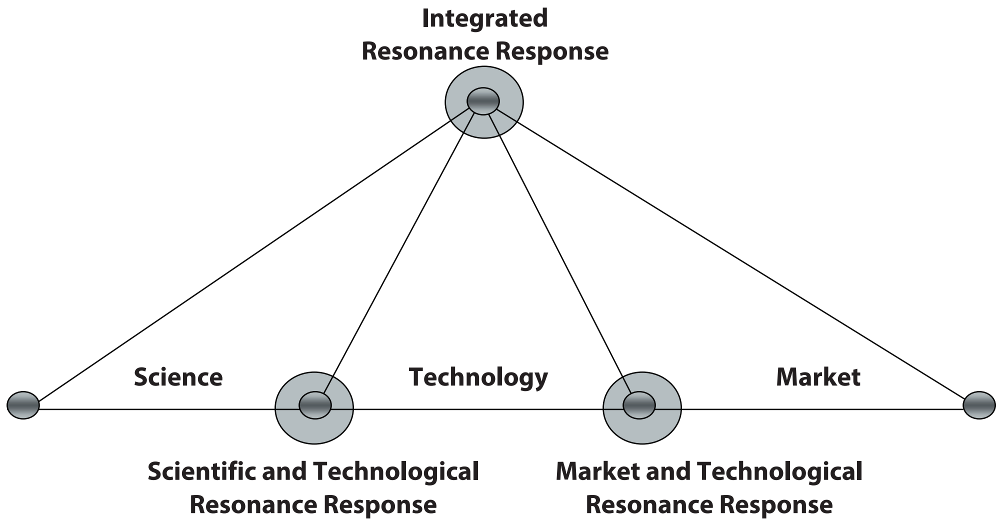

Fig. 5. The Typology of Resonance Responses of the Economic System to Control Actions

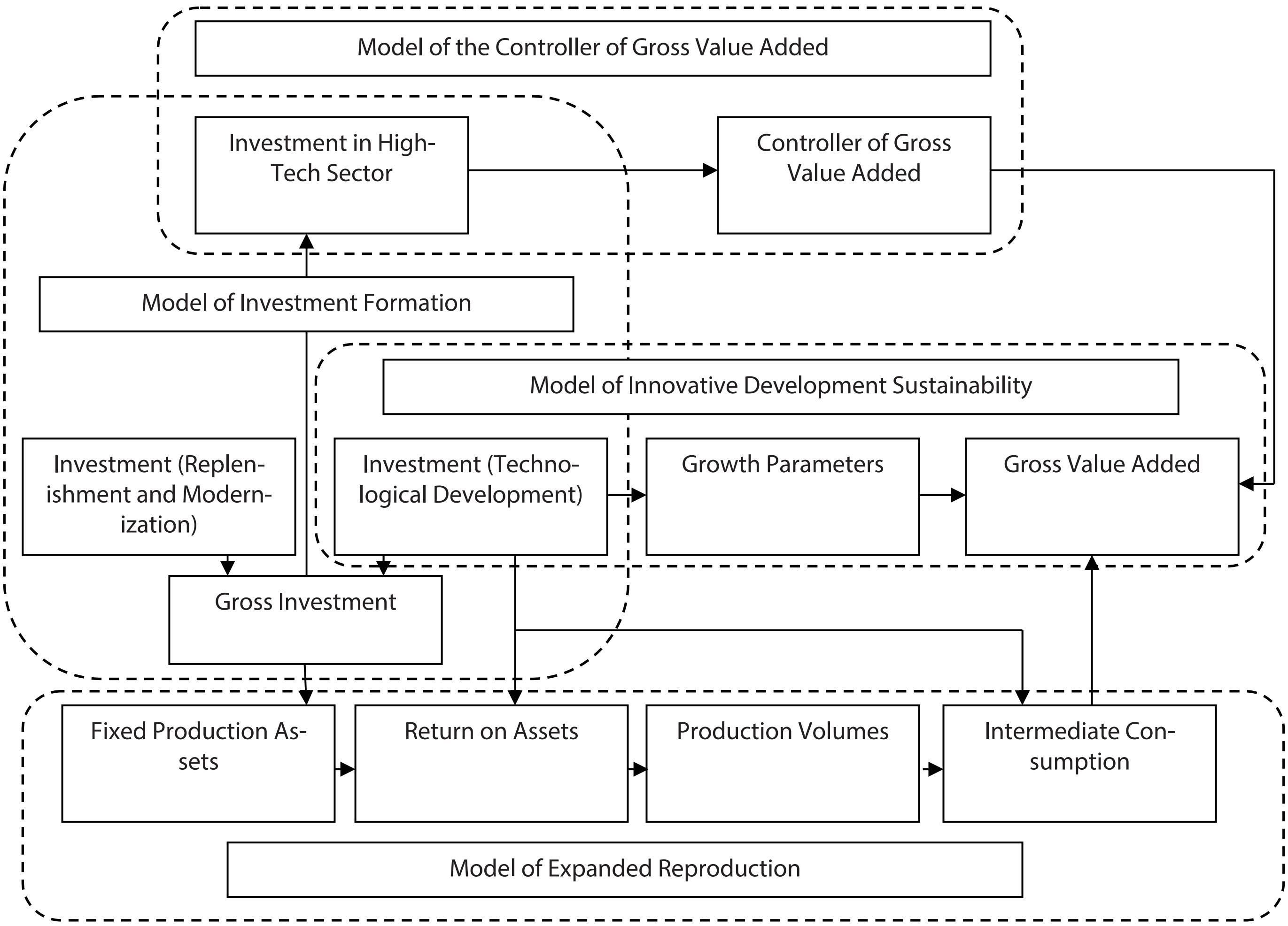

Fig. 6. *The Mathematical Set of the Mechanism of Innovation Resonance of the Economic System*

existing technology for the output of traditional products (*M*); 2) Technological development in the form of R&D costs and related expenditure for the acquisition of fixed assets and technology (*R*). Therefore, the volume of investment in fixed capital is defined as the sum of investment areas.

Accordingly, there are two groups of investors: conservatives and innovators. The change in the size of each subgroup can occur once, when it is related to changes in the products or technology used only by one investor, or many times.

A substantial role in this model should be played by a parameter that describes the investor preferences. The positive values of such parameter indicate the investor preference to the investment of *M* type and negative values—preference to the investment of *R* type. This parameter is time-dependent and has great importance in the formation of cyclic behavior of the mechanism of scientific and technological development. As the output variable, we will use the index value equal to the ratio of the difference between the investment volumes of *M* type and R type to their sum. It will be shown below that, under some reasonable assumptions, the dynamics of preference and investor factor, as well as the index, are rather accurately described by the system of two differential equations of first order.

The model allows determining the investment volume by industry sectors and reproduction sectors of the economy. In addition, an important outcome of the model will be the allocation of investment resources by areas to maintain the existing capacity and ensure the innovative development. The growth rates and volume of R&D investment define two key parameters of long-term innovative development: the return-on-assets factor and the share of value added in gross output.

2. The Dynamic Multi-Sectoral Model of Reproduction. This model describes the relationships that determine the output volume and value added by industry sectors and reproduction sectors. In the models, all calculations are made within the selected system of constant prices (usually, the prices of the year of planning). This model includes two group of relationships: macroeconomic relationship for building the scenarios based on the analysis of the most common proportions, limitations and elasticities; system of inter-sectoral and balance relationships that allow to obtain a consistent long-term quantitative assessment of the dynamics and structure of production by industry sectors, as well as by reproduction sectors.

3. The Model of Adaptive Control of Innovative Self-Development of Regional Industrial System. As any other dynamic system, the regional industrial system is a structure with feedback. In technical terms, this means that, in addition to its executive core (which represents the process of innovative self-development) and control unit, it has a feedback mechanism. The purpose of this element is to develop specific recommendations for the base control unit by using the measurements of obtained results.

In a regional economy, such information relates, in most cases, to strategic and tactical decisions in the area of investments in the high-tech industry sector, expenditure on funding the measures to stimulate scientific and technological progress, particularly, the development and adoption of new technology and resource-saving measures. In addition, the feedback unit allows receiving ongoing information on the effectiveness of decision-making and assessing the possible options for their change. If only the values of system parameters are changed in this process, such system is called a "self-adjusting," and if new elements appear or old elements become destroyed in a system, such system is called "self-organizing." With regard to the innovative development, it may be noted that the characteristics of the external environment and those of the object (region) itself can never be accurately predicted, which results in a situation of uncertainty. From the viewpoint of control theory, this means that the object parameters and environment parameters will change throughout the control process, so the control unit of the innovative self-development should be able to achieve three tasks: 1) Monitoring the object to identify (determine) the changing values of its parameters; 2) Synthesizing the algorithm of controller's work, under known parameter values, to ensure the required quality of system's activity; 3) Designing the controller, which implements the synthesized algorithm [28].

From a technical viewpoint, these tasks must be performed automatically, without human intervention. In other words, if the object parameters are not known in advance but remain constant, the tasks can be implemented at the design stage, and if its characteristics vary over time, the tasks should be addressed under the conditions and activity rhythm that are natural for the object. This means that the controller's algorithm must transform itself during the system operation by adapting (self-adjusting) within a rather short period to the changing environment and object parameters so that the quality of the latter's work remains unchanged [29].

4. The Model of Sustainability of Innovation Dynamics and Expanded Reproduction. The model of sustainability of innovation dynamics and expanded reproduction is intended to assess the sustainability of innovative development of the economic system. As it is known, the economic systems cannot remain in a state of stable equilibrium, and their normal state is dynamic equilibrium. The transition from one equilibrium state to another never happens instantly. Any exogenous shock gives rise to a chain of events that only ultimately leads to the establishment of a new dynamic equilibrium. The scenario of future events can be understood only be examining the process of their development.

This is the logic of methodological approach used in the mathematical set of the mechanism of innovation resonance of the economic system.

Mathematical Formalization of the Model of Innovation Resonance

The Model of Investment Volume Formation by Industry Sectors. As we already noted, the investment resources have two investment areas: 1) Replenishment and modernization of fixed capital within the existing technology for the output of traditional products (M_t); 2) Technological development in the form of R&D expenditure and related costs for the acquisition of fixed assets and technology (R_t). Therefore, the volume of investment in fixed capital is defined as the sum of investment areas:

$$I_t = M_t + R_t \tag{3}$$

The source of investment in fixed capital is provided by the net income of economic agents for the past period which, at the macro-economic level, represent the gross value added (Y_t). Let's introduce a parameter γ_i describing the share of investment in gross value added and we will obtain the equation for investment:

$$I_t = M_t + R_t = \gamma_1 Y_{t-1} + \gamma_2 Y_{t-1}. \tag{4}$$

It is clear that the proportion of such allocation affects the amounts of investment directed for various purposes, which ultimately affects the amount of gross output ($V_{i,t}$) and gross value added (Y_t).

The industrial enterprises find it profitable to increase their capacity in the production of consumer goods or means of production depending on market prices, which points them towards the future investment area (γ_1 and γ_2), thereby increasing their profit. As a characteristic of investor preferences, we can use the ratio of the difference between the investment volumes of M type and R type to their sum.

$$\begin{cases} I_t = M_t + R_t, \\ k = \dfrac{M_t - R_t}{M_t + R_t}. \end{cases} \tag{5}$$

After resolving this system of equations, we obtain the following result:

$$M_t = \frac{(1+k)I_t}{2}; \;\; R_t = \frac{(1-k)I_t}{2}. \tag{6}$$

The Dynamic Multi-Sectoral Model of Reproduction. For each time period, the dynamics of changes in fixed production assets are calculated on the basis of their retirement and allocation of investment from various sources to their replenishment and modernization. The embodiment of these investments is performed by taking into account the time lag:

$$F_{j,t} = (1-\alpha)F_{j,t-1} + l\left(M_{ij,t} + R_{ij,t}\right) + (1-l)\left(M_{ij,t} + R_{ij,t}\right), \; j = 1, \dots, n, \tag{7}$$

where α is the asset retirement factor; l is the time lag factor.

The calculation involves either the types of activity or four reproduction sector (consumer, high-tech, traditional, infrastructure sectors).

To determine the volumes of gross output for each type of activity and each reproduction sector, we will use the return-on-assets factor, which in turn affects R_t in each sector:

$$V_{j,t} = f_{j,t} F_{j,t}, \tag{8}$$

where f_j is the return-on-assets factor in each industry sector or each reproduction sector.

The return-on-assets factors are determined by taking into account the aging of equipment and investment in technological development of production:

$$f_{j,t} = f_{j,t-1}(1-\mu)\left(1 + \frac{\beta R_t}{M_t + R_t}\right), \tag{9}$$

where μ is the equipment aging factor, β is the factor characterizing the impact of an innovative component of investment on return on assets.

We determine the volumes of gross value added based on intermediate consumption, which is also affected by R_t:

$$Y_{j,t} = (1 - s)_{j,t} V_{j,t}, \tag{10}$$

where s_j is the share of intermediate consumption in the output of each industry sector or each reproduction sector.

Thus, the gross regional product will be calculated by using the following formula:

$$Y_t = \sum_{j=1}^{n} (1 - s)_{j,t} \left[f_{j,t-1} (1 - \mu) \left(1 + \frac{\beta \gamma_2 Y_{t-1}}{\gamma_1 Y_{t-1} + \gamma_2 Y_{t-1}} \right) \right] \times$$
$$\times \left[(1 - \alpha) F_{j,t-1} + l (\gamma_1 Y_{t-1} + \gamma_2 Y_{t-1}) + (1 - l)(\gamma_1 Y_{t-1} + \gamma_2 Y_{t-1}) \right]. \tag{11}$$

GDP (*GRP*) growth rates and industrial production indexes are the key indicators of economic and technological development:

$$g_j = \frac{V_t}{V_{t-1}}, \tag{12}$$

$$G = \frac{Y_t}{Y_{t-1}}. \tag{13}$$

The formula (11) demonstrates that *GDP* (*GRP*) growth rate makes a substantial impact on the following parameters: investment growth rate by industry sectors (reproduction sectors); investment areas for investment resources, primarily, the investment in innovation; fixed asset retirement factors; return-on-assets factors; share of intermediate consumption in the output; investment time lag.

The Model of Adaptive Control of Innovative Self-Development. As we understand, the purpose of adaptive control of innovative development is to ensure the capacity of the economic system to function effectively in the ever-emerging new conditions caused by the innovation resonance. Usually, the feedback unit is called "controller," while a set that includes the controlled object, feedforward unit and controller is called the "main control loop," and the feedback-based control process is called "controller algorithm" [30]. The most common method of using information in a feedback circuit is the rigid control scheme, where the recommendations to change the decisions are directly linked to deviations of actual results from planned results by using fixed factors (feedback parameters). The use of this scheme can be rather effective, if the state of the external environment, as well as the state of the object, remain stable or experience a relatively small change and predictable change, in other words, the situation is rather definite.

Let's build a model of adaptive control of the innovative development of the economic system. Suppose that, in a certain period t, the regional system has the following characteristics: F_t is the cost of fixed production assets; Y_t is the gross product (the sum of added values by reproduction sectors); I_t is the investment in fixed capital.

The main ratios of system dynamics are as follows:

$$Y_t = f \times F_t \tag{14}$$

$$F_t = (1 - \alpha) F_{t-1} + I_t, \tag{15}$$

where f is the return-on-assets factor for value added, α is the asset retirement factor.

In this case, I_t is the control action affecting the process, that is, the controller algorithm. Let's assume that the purpose of control is to achieve the *GDP* (*GRP*) target at the level of C. Then, in a state of complete certainty, the controller algorithm is as follows:

$$I_t = f^{-1} \left(C - f (1 - \alpha) F_{t-1} \right). \tag{16}$$

In economic practice, many factors, on which depend the parameters f and α, are either not available for direct measurement, or may vary over time in a constant way (for example, the return on assets may change following a transition to new equipment). In this regard, we accept the following definition: the control process can be called self-organizing, if the reduction of a priori uncertainties, that leads to effective control, is achieved with the information obtained in the control process, from successive observations of available input and output signals. [28] This self-organization is achieved: a) by decreasing the degree of uncertainty in describing the dynamics of the object (the self-organizing process of parametric adaptation); b) reducing the uncertainty directly related to the improvement of the system quality (functional and adaptive self-organizing process). In this case, the information obtained from the object of control is used directly by the control unit and corresponding performance evaluation unit. Next, we will proceed from the assumption that the values of Y, F, and I are at all times available for measurement and the parameters are determined by measuring the input and output values.

Therefore, the main control unit performs the following actions: preliminary assessment of the economic effectiveness of investment in high-tech sector; assessment of the contribution made by the high-tech sector in *GDP* (*GRP*); updated assessment of economic effectiveness that includes the local methods of incentives; systemic (synergistic) assessment of the high-tech sector's effectiveness.

As a result, the adaptive controller emerges always when it is necessary to strictly maintain the output value, and the conditions of the external environment are unpredictable. In this case, the feedback circuit usually experiences some time delays, which in technical units can be modeled by using the inertia links. The process of achieving the planned output signal represents an asymptotic approximation and can be stretched in time.

As the economic dynamics experience mostly qualitative change, while the information comes in a highly aggregated form, in this case, it is advisable to use built-in controllers proposed by Bagrinovsky [28]: reducing the interest rate on bank loans when there is a need of additional investment; reducing VAT when there is a need of additional supplies of raw materials; increasing VAT on goods in high demand; reducing the payments on shares, etc.

However, in economic processes, especially those involving the innovation, the response to the deviation is usually very slow and can be stretched over a long period of time (if it ever happens). In this case, a substantial role should be played by natural market processes: a profitable production or investment attracts investors; competition reduces the profitability, which forces the investors to look for new areas of profitable capital investment.

The Model of Sustainability of Innovation Dynamics and Expanded Reproduction. It was noted above that the impetus for the development of the economic system is provided by innovative dynamics, the qualitative characteristics of which are R&D expenditure, their structure and funding sources, as well as their ratio to gross value added.

Let's build a model of sustainability of innovation dynamics and expanded reproduction, where the initial assumption will be the continuous nature of financial flows and innovative product flows. The flowchart of such model is based on the fact that the initial flow of R&D expenditure creates a new production process or improves the old production process, which results in generating the material flow of innovative products. This is simultaneously accompanied by the creation of financial flow from innovation activities represented by innovation profit, which is defined as the difference between the innovation revenue and expenditure on manufacturing innovative products. When we take into account the calculation of gross value added for primary income, the main part of which is the profit, we can acknowledge the contribution of the innovation process to expanded reproduction. However, this same profit is a source of funding for new R&D.

This creates a closed algorithm of cross-impact between R&D expenditure and growth of gross value added, in which the gross value added is reduced by the amount of R&D expenditure, while R&D expenditure, in turn, serves as a source of profit growth and, accordingly, the growth of value added. It is in this process that occur both the innovative development and change of technological paradigms.

For quantitative description of the process, we will clarify the symbols used above and introduce a number of new symbols:

R_n is R&D expenditure in n-th year, R_{n+1} is R&D expenditure in $n+1$-th year, $R_{\max}$ is the maximum possible R&D expenditure in the economic system determined by market constraints.

Y_n is the gross value added (*GRP* or *GDP*) in n-th year, Y_{n+1} is the gross value added in $n+1$-th year, $Y_{\max}$ is the maximum possible gross value added in the economic system determined by the resource constraints.

d_n is the share of profit from innovative products in the gross value added in n-th year, d_{n+1} is the share of profit from innovative products in the gross value added in $n+1$-th year, in this case, (dY_n) is the innovation profit.

P_n is the innovation profit in n-th year, P_{n+1} is the innovation profit in $n+1$-th year, $P_{\max}$ is the maximum possible innovation profit in the economic system determined by market constraints.

g_Y is the growth parameter of gross value added.

g_R is the growth parameter of R&D expenditure.

k_Y is the specific value added per unit of innovative products.

k_R is specific R&D expenditure per unit of innovative products.

m is the factor for the transformation of value added into the new influx of R&D expenditure.

The growth of gross value added can be defined as $\frac{Y_{n+1}-Y_n}{Y_n}$, moreover, as the value added increases and approaches $Y_{\max}$, the growth in each subsequent period should decline. In this case, the dynamics of gross value added can be defined as follows:

$$Y_{n+1} = Y_n + Y_n g_Y \left(1 - \frac{Y_n}{Y_{\max}}\right). \tag{17}$$

However, the gross value added includes the innovation profit, which is the source of R&D expenditure formation. In this regard, the dynamics of innovation profit are as follows:

$$P_{n+1} = d_{n+1}Y_{n+1} = d_n Y_n + d_n Y_n g_Y \left(1 - \frac{d_n Y_n}{d_n Y_{\max}}\right). \tag{18}$$

Clearly, the part of the value added allocated to fund R&D expenditure will depend on the ratio of specific values (k_R/k_Y) and the factor for the transformation of value added into the new influx of R&D expenditure (m). In this case, the equation describing the change in gross value added will be as follows:

$$Y_{n+1} = Y_n + Y_n g_Y \left(1 - \frac{Y_n}{Y_{\max}}\right) - m\frac{k_R}{k_Y}R_n. \tag{19}$$

The equation describing the change of R&D expenditure can be prepared in a similar way, given that the maximum expenditure value R max is determined by the volume of gross value added in the economic system at this point in time, and by taking into account the specific values and the factor for transformation:

$$R_{\max} = Y_n \frac{k_Y}{k_R m}. \tag{20}$$

In this case, the equation describing R&D expenditure will be as follows:

$$R_{n+1} = R_n + R_n g_R \left(\frac{Y_n \frac{k_Y}{k_R m} - R_n}{Y_n \frac{k_Y}{k_R m}}\right) = R_n + R_n g_R \left(1 - \frac{m\frac{k_R}{k_Y}R_n}{Y_n}\right). \tag{21}$$

Innovation Resonance in Russian Industrialized Regions

The analysis of patterns in innovation dynamics represents a great interest in terms of understanding the economic resonance and strengthening the competitive advantages of industrialized regions. The study of technological structure in the industrialized regions revealed some patterns in the change of technological paradigm at the regional level, some of which may be considered as the momentum for innovation resonance. In particular, we are referring to the following. The change of technological paradigm and, accordingly, the innovation resonance begin within the structure of R&D expenditure, while the structure of output and *GRP* can change only after the change in the area of innovation. The capacity and prospects of the technological paradigm are most closely reflected in the structure of innovation product output. All this describes the internal fluctuations inherent to the economic system and is associated with the parameter r in equation (1). At the same time, as we noted above, the modulation of parameter C in equation (1) representing the state support measures leads to a shift in the curve and results in the resonance of functions. The concept of self-development of territories [31, 32] considers only regional measures of state support and their respective costs in the consolidated budgets of subjects of the Federation.

The analysis of existing support measures in the industrialized regions revealed that the standard set of measures (tax incentives, guarantees and sureties, subsidizing interest rates and Leasing payments, subsidizing the costs of engineering infrastructure, special economic zones, technology parks and industrial parks, support for small and medium-sized manufacturing business, etc.) is adopted at the regulatory level in all industrialized regions (Table 2). As we noted above, despite all this, some industrialized regions are facing severe problems of deindustrialization, and some are intensively developing and strengthening the industrial sector of their economy.

Table 2

Regional Measures of State Support in Individual Industrialized Regions

State Support Measures	Regions that strengthened their industrialized status			Newly Industrialized Regions		Traditional industrialized regions facing negative deindustrialization						
	Kaluga Region	Republic of Bashkortostan	Tula Region	Republic of Mari El	Kirov Region	Lipetsk Region	Krasnoyarsk Territory	Chelyabinsk Region	Vologda Region	Sverdlovsk Region	Samara Region	Nizhny Novgorod Region
Land Tax Benefits				+								
Property Tax Benefits	+		+	+	+	+	+	+	+	+	+	+
Profit Tax Benefits	+		+	+	+	+	+		+	+	+	+
Transport Tax Benefits				+		+			+	+		
Subsidies for Leasing Payments	+		+		+	+	+	+	+	+	+	+
Leasing Guarantees							+	+	+		+	
Leasing of State Property											+	
Loan Guarantees	+		+	+	+	+	+	+	+	+	+	+
Subsidizing Interest Rate on Loans	+	+	+	+		+	+	+	+	+	+	+
Preferential Investment Loans										+		
Sureties			+				+	+		+	+	
Grants to Small Businesses	+	+	+	+		+	+	+	+	+	+	+
Loans to Small Businesses	+		+	+	+		+	+	+	+		
Subsidies for Connection to Infrastructure	+		+			+						
Business Incubation Services			+	+	+			+	+	+		
Lease of State Property				+	+							+
Industrial Parks and Technology Parks			+	+	+					+	+	
Energy Efficiency						+					+	
Subsidies for Localization						+					+	
Subsidies for Energy Cost Compensation						+			+			
Subsidies for Professional Development			+			+			+		+	
Social Entrepreneurship			+		+	+			+	+		
Participatory Interest in Authorized Capital			+				+				+	
Venture Financing	+									+	+	
Subsidies for International Standardization						+			+			
Subsidies for Innovation	+			+		+		+		+	+	
Subsidies for Promotion	+		+		+	+		+				+

We believe that the problem lies primarily not in what kind of support measures have been stated at the regulatory level, but what funds are allocated in the regional budget for implementing these support measures. The study revealed that, in newly industrialized regions and regions that strengthened their industrialized status, the amount of expenditure in regional budgets is 1.5 times higher than in industrialized regions with plummeting share of the industrial sector (Table 3). While in the newly industrialized regions the amount of expenditure in regional budgets is on average 42.5 thousand rubles per 1 million rubles of industrial output, in the deindustrialized regions this figure stands at 29.6 thousand rubles. This is exactly what leads to alignment between the dynamics of economic and innovation development and the emergence of innovation resonance in newly industrialized regions, because in all industrialized regions the ratio of investment and R&D expenditure to GRP is roughly equal (Table 3).

Table 3

Individual Indicators of Russian Industrialized Regions, 2013

Subject of the Russian Federation	Amount of expenditure to support the industrial sector in the consolidated budget of the subject of the Russian Federation per 1 million rubles of industrial output, thousand rubles	Investment in fixed capital as % of GRP	R&D expenditure as % of GRP	Annual average index of industrial production for 2010–2013, %
Regions that strengthened their industrialized status				
Kaluga Region	26.2	33.3	2.79	119.3
Republic of Bashkortostan	24.0	20.2	0.61	107.5
Novgorod Region	55.0	26.1	0.68	110.0
Tula Region	32.3	27.2	0.79	114.1
Newly Industrialized Regions				
Perm Territory	17.5	18.1	1.20	111.2
Republic of Mari El	47.9	26.9	0.15	110.1
Volgograd Region	24.8	23.7	0.80	105.2
Kirov Region	66.3	23.8	0.48	107.7
Chuvash Republic	50.8	30.1	0.65	109.9
Ryazan Region	47.5	27.0	0.56	108.7
Traditional industrialized regions facing negative deindustrialization				
Lipetsk Region	29.1	31.7	0.07	108.7
Krasnoyarsk Territory	30.1	32.0	0.82	102.4
Omsk Region	23.7	21.8	0.65	105.6
Yaroslavl Region	47.2	25.0	1.36	105.7
Chelyabinsk Region	22.9	22.9	1.40	105.4
Vologda Region	26.2	42.4	0.10	105.5
Sverdlovsk Region	24.7	23.7	1.37	108.7
Samara Region	28.9	22.6	1.95	107.3
Vladimir Region	35.0	21.4	1.25	108.4
Nizhny Novgorod Region	28.2	30.7	4.44	109.7

As we can see, the existence of stated support measures does not provide a guarantee of accelerated industrial development. At the same time, state expenditure on industrial development is not a panacea. The state expenditure provides only a momentum that attracts private sector investment, reduces risks and increases the competitiveness of the region. According to Expert Rating Agency, the investment risks are substantially lower in the newly industrialized regions and regions that strengthened their industrialized status.

For deindustrialized regions, the only indicator signaling the real capacity for new industrialization, is the index of knowledge intensity of GRP (ratio of R&D expenditure to GRP, %). Among the deindustrialized regions, there is a distinct group of regions where this indicator exceeds 1 %, including

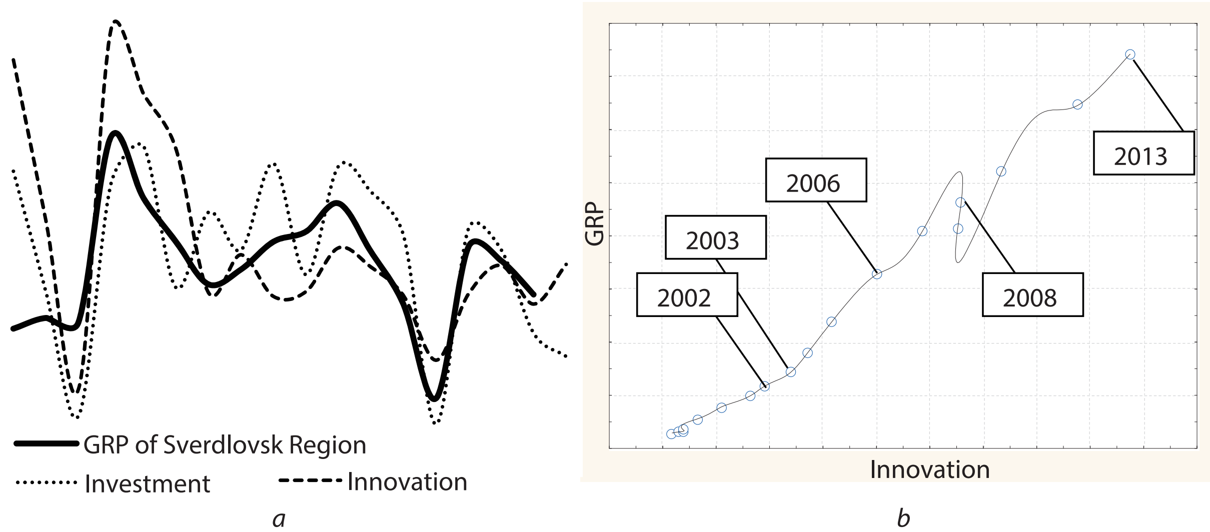

Fig. 7. *The dynamics of GRP, investment in fixed capital and R&D expenditure in Sverdlovsk Region over 1996–2013*

Nizhny Novgorod Region (4.4 %), Samara Region (2.0 %), Yaroslavl Region (1.4 %), Chelyabinsk Region (1.4 %), Sverdlovsk Region (1.4 %), Vladimir Region (1.3 %).

This confirms the hypothesis of catalytic role played by the state support in innovation resonance that leads to the alignment of economic and innovation dynamics. In the regions with high level of state expenditure per 1 million rubles of industrial output, the average index of industrial production (IIP) is substantially higher. In the group of regions that strengthened their industrialized status, the average IIP is 113 % PPIS; in newly industrialized regions, 109 %; and in the deindustrialized regions, 106 %.

Also, it is quite interesting to consider the resonance response to state support measures in the context of Sverdlovsk Region, a typical industrialized region. Fig. 7 shows the turning points, where the economic dynamics (linked graph of GRP and innovation) change their angle in response to state support measures introduced in the region:

1) 2002: Enactment of the Law of Sverdlovsk Region On the Rate of Corporate Profit Tax for Individual Categories of Taxpayers in Sverdlovsk Region No. 42-OZ of November 29, 2002, that established the regional benefits;

2) 2003: Enactment of the Law of Sverdlovsk Region On the Introduction of Corporate Property Tax in Sverdlovsk Region No. 35-OZ of November 27, 2003, that established the regional benefits;

3) 2006: Introduction of the tax benefits for companies that have the status of participant in the priority investment project of Sverdlovsk Region for new construction in accordance with the Law of Sverdlovsk Region No. 43-OZ of June 30, 2006;

4) 2007: Elaboration of strategic document Strategy of Socio-Economic Development of Sverdlovsk Region for the Period until 2020 No. 873-PP of August 27, 2008, that defines the priorities for the development of Sverdlovsk Region;

5) 2008: Financial and economic crisis;

4) 2013: Approval of the state program of Sverdlovsk Region Development of the Industry and Science in Sverdlovsk Region until 2020, a strategic sectoral document No. 1293-PP of October 24, 2013, that defines such financial measures to support the industrial sector, as the provision of subsidies to the companies of industrial sector of Sverdlovsk Region to compensate the costs associated with the implementation of R&D in the area of industrial production; provision of subsidies to legal entities to compensate the costs associated with the implementation of R&D in the area of nanotechnology; provision of subsidies to legal entities to compensate the costs associated with performance of R&D in the area of nanotechnology; provision of subsidies to the residents of technology parks in Sverdlovsk Region to compensate the costs associated with production and sale of innovative products; provision of subsidies to companies in the industrial sector of Sverdlovsk Region to compensate the cost of interest payments on loans received in Russian credit institutions for implementation of investment projects in the amount no exceeding 2/3 of refinancing rate of the Central Bank of the Russian Federation established at the time of loan agreement; provision of subsidies to companies in the industrial sector of Sverdlovsk Region to compensate the costs of implementing in their production process (practical

activities) the new products (goods, works, services) that have been modified or improved in terms of technology, production processes, new or improved technological processes or ways of production (provision of services).

Conclusion

The research study proved that the quantitative essence of innovation dynamics is the innovation response, which is understood in terms of the synergistic approach and reflects the non-linear relationships of non-equilibrium processes of capital renovation, technological change, social and economic growth in economic systems. The hypotheses advanced on the existence of this phenomenon have been proven with mathematical models.

The article examined the Russian industrialized regions, which are the basis for the development of the national economy. Today, 20 industrialized regions account for a third of the total industrial production in Russia. It is in industrialized territories that occurs the transformation of the technological structure of the economy, change of techno-economic paradigms, modernization of production and consumption. The research study showed that Russian industrial sector as a whole has a fairly high innovation capacity. However, there are significant variations in the indicators of innovation dynamics of this capacity across different regions and, as a result, the hypothesis of uneven economic development in different types of industrialized regions was proved empirically. The analysis of development capacity of industrialized regions confirmed the hypothesis on the need to develop an individual development trajectory for specific types of regions.

Given their resource capacity, as well as the accumulated economic and innovation dynamics, some regions should develop towards new industrialization, some regions will choose a strategy for modernization and support of traditional industries, while other industrialized regions have the objective grounds to become the territories of service and consumption. We also want to emphasize that, in implementing any variant or combination of variants, the local initiatives will be insufficient to address the problems of regional restructuring. The functional industrial policy implemented in the regions should become a key catalyst of innovation resonance. The approaches to assess the effectiveness of such policy have been substantiated on the basis of empirical analysis. This article begins a series of articles on innovation resonance. Our future research studies will be aimed at proving the performance of this set of models by using the historical data and simulations.

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